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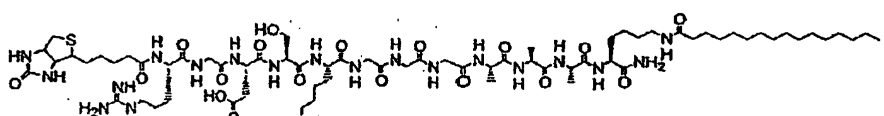

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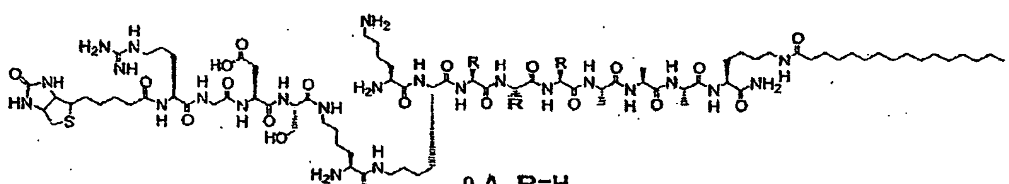

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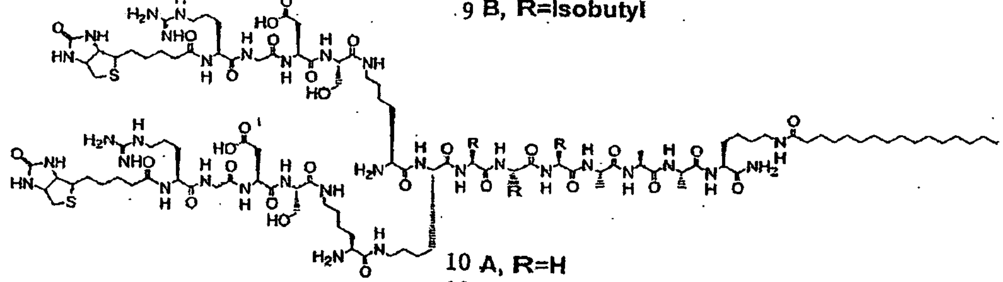

10 A, R=H
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(57) **Abstract:** Branched peptide amphiphilic compounds incorporating one or residues providing a pendant amino group for coupling one or more epitope sequences thereto, such compounds and related compositions for enhanced epitope presentation.

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BRANCHED PEPTIDE AMPHIPHILES, RELATED EPITOPE COMPOUNDS AND SELF ASSEMBLED STRUCTURES THEREOF

This application claims priority benefit from application serial no. 60/527,442 filed December 5, 2003, the entirety of which is incorporated herein by reference.

The United States government has certain rights to this invention pursuant to Grand No. DE-FG02-00ER54810 from the Department of Energy to Northwestern University.

Background of the Invention.

Molecular recognition among ligands and receptors in biology requires appropriate presentation of epitopes. Cellular adhesion ligands in extracellular matrix play a critical role in cell adhesion and attachment, which affect cell proliferation, differentiation and maintaining regular metabolic activities. Recently, there has been great interest in designing scaffolds that mimic cellular structures with artificial epitopes, in order to trigger biological events important in regenerative medicine or targeted chemotherapy. Differences in cellular response have been reported with changes in distribution and structural presentation of the signals on these artificial cell scaffolds. For, example, varying the nanoscale separation between cell adhesion ligands has been found to improve the recognition of signals and subsequent proliferation of the cells. Among the various methodologies used to synthesize biomaterials, self-assembly is a particularly attractive tool to create scaffolds from solutions of molecules that can encapsulate cells and assemble in situ.

Summary of the Invention.

In light of the foregoing, it is an object of the present invention to provide a molecular architecture for delivery and presentation of biologically active epitopes, thereby addressing various concerns in the art, including those outlined above. It will be understood by those skilled in the art that one or more aspects of this invention can meet certain objectives, while one or more other aspects can meet certain other objectives. Each objective may not apply

equally, in all its respects, to every aspect of this invention. As such, the following objects can be viewed in the alternative with respect to any one aspect of this invention.

It is an object to the present invention to provide compounds and related compositions capable of self-assembly for structural presentation of a wide range of bioactive epitopes.

It can be another object of the present invention to provide molecular structures comprising compounds enhancing epitope presentation and corresponding signal recognition.

It can be another object of the present invention to provide a wide range of amphiphilic peptide compounds having a three-dimensional structure for separation of epitopes/cell adhesion ligands, such compounds capable of self-assembly, under physiological conditions, for presentation and distribution of such epitopes/cell adhesion ligands.

Other objects, features, benefits and advantages of the present invention will be apparent from this summary and certain embodiments described below, and will be readily apparent to those skilled in the art having knowledge of various amphiphilic compounds, self-assembly techniques and peptide synthesis. Such objects, features, benefits and advantages will be apparent from the above as taken into conjunction with the accompanying examples, data, figures and all reasonable inferences to be drawn therefrom, alone or with consideration of the references incorporated herein.

In part, the present invention can comprise a non-linear peptide amphiphile compound. Such a compound comprises a peptide component comprising at least one amino acid residue comprising a pendant amino group. The amino group can be coupled to or bonded directly with a component non-linear width the length or longitudinal axis of the peptide component. Providing such a compound amphiphilic character, the peptide component is coupled to or bonded directly with a hydrophobic component. As discussed more fully below, the aforementioned amino acid residue can be of a naturally or non-naturally occurring amino acid. Likewise, the pendant amino group can

be derived from another functional group before or after incorporation into the peptide component. Further, as would be understood by those skilled in the art, such pendency can comprise any group functionally capable of coupling or bonding directly to another component so as to provide the compound a branched or non-linear configuration. Regardless, in certain embodiments, such a residue can be of one of several naturally-occurring amino acids, including but not limited to lysine.

Incorporation of at least two such residues can be used to couple to the peptide component one or more bioactive epitope sequences. Such sequences include but are not limited to those provided in co-pending application serial no. 10/368,517 filed February 18, 2003 (International publication no. WO 03/070749) and in co-pending application entitled, "Self Assembling Peptide Amphiphiles and Related Methods for Growth Factor Delivery" filed concurrently herewith on December 6, 2004, each of which is incorporated herein by reference in its entirety. Accordingly, such sequences can be selected from known and/or available cellular adhesion ligands relating to e.g., cell proliferation, differentiation and/or metabolism, biomimetic variations thereof and/or binding sequences interactive with a range of growth factors and/or related morphogenetic proteins, peptides or other associated molecular components, such binding sequences as can be identified through known phage display processes, including but not limited to those described in the aforementioned co-pending, co-filed applications.

As described more fully below, such epitope sequences arranged and/or configured (e.g., in a further branched or cyclic configuration) as would be known in the art, can be coupled to or bonded directly with the peptide component of an amphiphilic compound of this invention at or about the N-terminus thereof. Whether or not such a residue is of lysine or another such naturally-occurring amino acid, epitope number and identity can be varied depending upon such residues and available, pendant chemical function. Likewise, length or sequence of the peptide component can be varied depending upon desired flexibility, charge and/or capacity for intermolecular

attraction or bonding. The hydrophobic component of such compounds can also be varied (e.g., ~ C_6 - ~ C_{22} alkyl or substituted alkyl, saturated or unsaturated, etc.), limited only by resulting amphiphilic character and affect on associated systems of such compounds.

As described more fully below, the present invention relates to branched peptide amphiphiles (PAs), embodiments of which can self assemble into nanofibers under physiological pH conditions. For example, with the addition of pH 7.4 phosphate buffer and in basic conditions, or otherwise under physiological conditions, such PAs with the branched peptide sequence self-assemble into cylindrical micelles which form self-supporting gel samples. Such PAs with the branched peptide sequence may result in a better exposure of a biologically active peptide sequence on the surfaces of self assembled nanofibers. Peptide amphiphiles having a branched peptide component can also permit presentation of multiple epitopes from a single peptide amphiphile. Examples of such biologically active peptide epitopes include but are not limited to sequences comprising Arg-Gly-Asp-Ser (RGDS), Pro-His-Ser-Arg-Asn (PHSRN), Ile-Lys-Val-Ala-Val (KVAV), and Tyr-Ile-Gly-Ser-Arg (YIGSR). Such peptide sequences or epitopes may be used but are not limited to imparting cell adhesion activity or cell receptor binding properties to such compounds or assemblies.

One embodiment of the present invention can comprise a branching peptide amphiphile having an epitope, that when self assembled, places one or more epitopes at the periphery of a nanofiber configuration with synergistic sequence(s) promoting cell adhesion. Another embodiment of the present invention can comprise the presence of more than one biologically functional group on a branched PA compound. Without restriction to any one theory, it is believed that branching permits better access and presentation of the group(s) and/or epitope(s) on the surfaces of an assembly thereof.

Another embodiment of this invention can comprise a treatment method comprising cellular administration of any of the present peptide amphiphiles for purpose of but not limited to tissue repair or bone growth. In

certain embodiments, the peptide amphiphiles self assemble before administration, or self assemble upon or after cellular contact or administration to a cellular environment. Without limitation, self assembled nanofibers which comprise the peptide amphiphile with the branched peptide portion may also comprise cells or a therapeutic agent or composition in association with the hydrophobic component of a micelle or one or more epitopes on the surface of the micelle which may be delivered as part of a therapy to a cell sample or to a mammalian/patient cellular or tissue site. Such embodiments can encapsulate, have bonded to their epitopes or otherwise present various cells and or therapeutic agents such as but not limited to anti-inflammatory compounds, chemotherapeutic compounds, and combinations of these.

The peptide amphiphiles including the branched peptide sequence can be used in a medical applications with different epitopes chosen according to their desired functions. Self assembled materials made from these peptide amphiphiles may be used as a scaffolding for tissue transplant, reconstructive tissue growth, or tissue growth *in vitro* or *in vivo*. The amphiphilic character of the peptide amphiphiles with the branched peptide sequence can be used to encapsulate hydrophobic drugs in the core of nanofibers. In addition, representing use of a spectroscopic probe, a Gd complexing DOTA molecule may be attached as one of the epitopes of the nanofibers for magnetic resonance imaging studies of tissues or cells *in vitro* or *in vivo*.

Brief Description of the Drawings.

In part, other aspects, features, benefits and advantages of the embodiments of the present invention will be apparent with regard to the following description, appended claims and accompanying drawings where:

FIG. 1 includes illustrations of the molecular structures of peptide amphiphiles (1), (2), and (3) of the present invention;

FIG. 2 includes illustrations of the molecular structures of peptide amphiphiles (4) and (5) of the present invention;

FIGS. 3-4 includes illustrations of the molecular structures of peptide amphiphiles (6) and (7) of the present invention;

FIG. 5 provides amphiphile structures 8-10; and

FIGS. 6-7 schematically illustrate synthesis of representative peptide amphiphile compounds.

Detailed Description of Certain Embodiments.

Embodiments of the present invention include peptide amphiphiles with a branched peptide sequence which may self assemble to form micelles. Such micelles include but not limited to cylindrical fibers or nanofibers. Although the self assembled structures disclosed herein are nanofibers, the present invention includes any self assembled structure and the present invention is not limited to nanofibers.

In the present invention, the peptide amphiphiles can have more than one branch to which various groups can be coupled or chemically bonded. These groups or epitopes can be biologically active and can include but are not limited to amino acids, a cell adhesion peptide sequence, peptides, peptide and protein sequences derived from a phage display process, a fluorescent probe, a radiological probe, a magnetic probe, and combinations of these. As illustrated by example only in FIGs. 1-4, peptide amphiphiles with a branched peptide component can include but are not limited to: those with one or more peptides or amino acid residues (e.g., PA6) linked to a branching amino acid such but not limited to as lysine (K); those with an epitope and a side chain peptide or amino acid residue (e.g., PAs 1, 4 and 7) linked to a branching amino acid such but not limited to as lysine (K);. those with two or more of the same epitope (e.g., PA2) linked to a branching amino acid such but not limited to as lysine (K); and those with multiple epitopes (e.g., PAs 3 and 5) linked to a branching amino acid such but not limited to as lysine (K).

By way of example only, the peptide amphiphile (7) of the present invention has a hydrophobic component, which can be a C_{16} alkyl chain, and a branched peptide component. The peptide component comprises the branching

amino acid residue lysine (K) and the epitope (DOTA-KG-RGDS-K) as shown in Fig. 4 *vide infra:*

In PA7, the peptide component (K-LLL-AAA-(K)) is coupled toward the C-terminus with lysine to the hydrophobic component. The peptide component can have at least two components non-linear thereto via a branching amino acid (e.g., K). One or both of peptide branches can include a biologically active epitope such as but is not limited to amino acids, a cell adhesion sequence, a peptide, peptide and protein sequences derived from a phage display process, a fluorescent probe, a magnetic probe or combinations of these.

The presence of peptide amphiphiles with a branched peptide sequences in self assembled nanofibers may offer better exposure, accessibility, or availability of the epitopes on the branched peptide to external molecules. This accessibility can have important benefits for biomedical applications such as but not limited to tissue regeneration, scaffolds for tissue transplants, cell recognition, and reconstructive surgeries.

Presentation of a single RGDS sequence in a branching peptide (1) of the present invention is a non-limiting example of biologically active peptide amphiphiles of the present invention which are designed to be a more readily recognized epitope at the periphery of nanofibers self assembled from them. A linear PA of the prior art can contain only one epitope. In the branched systems of the present invention, more than one epitope can be used to improve biological activity. For this purpose, synergistic sequences of cell adhesive epitopes may also be synthesized on the same PA, as shown for example by (PA3) in FIG. 1 and by PA5 in FIG. 2. Currently, addition of ions or changing the pH to acidic or basic conditions are methods used to form the traditional PA nanofibers. The branched PAs of the present invention advantageously form nanofibers and self-supporting gels at neutral pH and under basic conditions. Nanofiber formation at physiological pH is a desirable property for most of the biological applications of such peptide amphiphiles. Multiple functional groups can be attached to these branched PAs via solid phase synthesis.

Fluorescent probes can be attached to the free amine groups of lysine amino acids. Also the free amine group at the hydrophilic surface of nanofibers made from peptide amphiphiles of the present invention would be available for other ion sensing probes. The DOTA branched PA7 is but one example of this type of peptide amphiphile compound. The Gd complexing DOTA moiety on branched PA7 may be useful relaxation studies for magnetic resonance imaging applications.

Various agents or reagents may be used to self assemble the peptide amphiphile of the present invention. Such agents may include but are not limited to complementarily charges peptide amphiphiles, acids or bases, multivalent ions, dehydration and combinations of these. Preferably the branched PAs of the present invention form nanofibers and self-supporting gels at, or upon achieving physiological pH or basic conditions.

Amino acids having pendent amino groups useful for coupling to other peptides can be used to synthesize the branched structure of the peptide amphiphiles of the present invention. One or more such residues can be incorporated into the peptide component to create multiple branching sites. Peptide amphiphile 1 in FIG. 1 has branching amino acid lysine on the backbone of the peptide amphiphile which forms a branch to an RGDS-K epitope and another lysine amino acid (K-). Where more than one branch is desired, multiple amino acids, each with a pendent side chain and/or amino group may be used as illustrated in FIG. 1 for peptide amphiphile (2). Lysine may be used to synthesize branches of the peptide amphiphiles in the present invention because it has two functional amine groups which may be used to modify its chemistry. However, the present invention is not limited to lysine, and other amino acids with two or more functional groups which may be converted to amines or other useful functionalities for solid phase synthesis of peptides may be used for the branching amino acid. For example, amino acid with amine side chains including but not limited to naturally occurring amino acids and non-naturally occurring amino acids such as beta or gamma amino acid may be used. Preferably the branching amino acids are chosen such that

they can that can be modified to form at least alpha and epsilon amine side groups. These alpha and epsilon amine side groups can be used to continue peptide synthesis of the branches. Orthogonal protecting groups can be used on the one or more amine side groups to enable different chemistry to be performed on them independently. For example, to attach the hydrophobic component, the orthogonal protecting group strategy may be used without harming the alpha amine protection. In this case, the epsilon amine protection may be removed and the alkyl chain coupled to the deprotected amino acid.

Branching may be increased by using multiples of a chosen branching amino acid. For example, one branching lysine can provide 2 active branching sites, an additional 2 lysines can provide 4 active branching sites, and an additional 4 lysines can provide 8 active branching sites.

Alpha and epsilon amine protection of the lysine residue(s) was selected according to the branch design. If two different branches are desired, Mtt group was used for lysine side chain protection. For growing the first branch, Fmoc group was removed without removing Mtt protection. After completion of the first branch sequence, the last amino acid was selected with a Boc protection which is resistant to the Mtt cleaving conditions. Mtt is then removed to grow the second branch of the PA. If two similar branches was desired, Fmoc side chain protected lysine was used to make the PA. Both Fmoc groups were removed by piperidine solution, and the two branches of the PA were made at the same time.

The branched PAs and self assembled micelles thereof can be used in tissue engineering, tissue reconstruction, synthetic vaccine design, drug delivery, magnetic resonance imaging and sensor applications. The amphiphilic character of these PAs can also be used to isolate single walled carbon nanotubes. For example, branched PA6, as shown in FIG. 3, can be used to encapsulate hydrophobic drug or other therapeutic molecules. The self assembled nanofibers which includes the peptide amphiphile with the branched peptide portion may also include cells or a therapeutic composition at the core of the micelle or coupled to one or more epitopes on the surface of

the micelle which may be delivered as part of a therapy to a cell sample or to a site on a patient that includes cells or tissue. Where the nanofibers are in the form of a pre-molded or pre-formed scaffold, the nanofibers may encapsulate or have bonded to their epitopes various cells and or a therapeutic composition such as but not limited to anti-inflammatory compounds, chemotherapeutic compounds, and combinations of these which may be delivered as part of a therapy to a cell sample or to a site on a patient that includes cells or tissue.

The PA compounds of the present invention can generally comprise, in certain embodiments, a hydrophobic alkyl component and a branched peptide component. The branched peptide component can comprise charged groups, epitopes, and biological signals by virtue of the arrangement and choice of the amino acid residues in the component. Hydrophilic amino acids may be charged and can be used to provide a degree of solubility in an aqueous environment. In an aqueous environment, such peptide amphiphiles have the ability to self-assemble into cylindrical micelles or nanofibers with the hydrophobic components tails oriented toward the center and with the generally hydrophilic functional peptide branched peptide exposed along the peripheral surface. The branched peptide component, is bulky relative to the hydrophobic component, giving the PA compound an overall conical shape. While not wishing to be bound by theory, it is thought that this shape as well as the hydrophobic and hydrophilic arrangement of the segments plays a critical role in PA self-assembly. With the branched peptide groups exposed along the length of the fiber, a bioactive epitope or biological signal can be presented to the environment.

To enhance the robustness of a PA compound, the peptide component can comprise one or more cysteine residues as shown in PA (6) in FIG. 3, coupled to a lysine amino acid (as shown) or other amino acids such as but not limited to alanine and or glycine. When assembled, the S-H ligands of neighboring cysteine residues are in close enough proximity to allow stable disulfide bond formation; exposure to oxidative conditions such as iodine or

oxygen leads to disulfide bond formation and cross-linking of the fibers. One versatile feature of such PAs is reversible cross-linking. The PA fibers can be disassembled using a reducing agent such as dithiolthreitol (DTT). The PA can otherwise be self-assembled, improving its adaptability for medical use.

The hydrophobic component can be a hydrocarbon, such as but not limited to an alkyl moiety or other structure which can be used to provide amphiphile function. The size of such a moiety may be varied, but in certain embodiments range from about and greater than C_6 in length. This component of the peptide amphiphile serves to create the slender portion of the PA molecule's conical molecular shape. Other chemical groups, such as triacetylenes, which provide hydrophobicity and a shape which allows self assembly to the peptide amphiphile may also be used. The hydrophobic component is covalently coupled or bonded to the peptide component, as described above.

The peptide component of the branched PA compound component can comprise, as discussed above, cysteine residues, if cross-linking is desired. Regardless, other amino acids such as but not limited to alanine, serine, or leucine may be used in this region (e.g. SLSL or AAAA as described in more detail herein). Such cysteine-free components may be more appropriate for in situ biological applications where the environment may be more difficult to regulate cross-linking. The SLSL modification to the system is expected to lead to a slower assembly of the nanofibers. Without wishing to be bound by theory, it is believed that the bulky leucine side chains may require more time to pack into the fiber. A slowed self-assembly may also have greater applications in a functional, in situ environment such as an operating room, where it may be advantageous to have delayed formation of the nano-fibers. The peptide component can also include residues such as but not limited to glycine to impart structural flexibility.

The peptide component can comprise any naturally or non-naturally occurring amino acid, including but not limited to a charged or hydrophilic amino acid such as lysine, serine, phosphorylated serine, diaminopropionic

acid, diaminobutyric acid, and aspartic acid—the choice of which can provide a charged peptide-amphiphile, such as PA6 shown in FIG. 3. Near physiological pH, such charged peptide-amphiphiles may be positively or negatively charged. The peptide component is a relatively bulky, charged segment of the PA compound, providing, with one or more branches, the widest region of the conical molecular geometry.

Self-assembly of mixtures of different PA compounds can also allow for the presentation of different amino acid sequences along the length of an assembled nanofiber of corresponding peptide components of varying length and/or amino acid sequence. Further, it is contemplated that self assembly of branched peptide amphiphiles of different sizes, or mixtures of branched peptide amphiphiles and filler peptide amphiphiles of different sizes, or combinations of these may be self assembled from nanofibers or other micelles having protruding peptide amphiphiles on the surfaces of the self assembled nanofibers or micelles.

Various peptide amphiphile compounds and the branched PAs of the present invention can be synthesized using preparatory techniques well-known to those skilled in the art, including those disclosed in the aforementioned co-pending published application and co-pending application serial no. 10/294,114 filed November 14, 2002 (International publication no. WO 03/054146), the contents of which are incorporated herein by reference in their entirety, and modifications of those techniques originally described by Stupp et al. *(See e.g.,* J.D. Hartgerink, E. Beniash and S.I. Stupp, *Science* 294, 1683-1688, 2001), which is also incorporated in its entirety by reference. The synthetic schemes set forth in these references may be applied to the present invention. Peptide amphiphiles may be in their fully protonated form, partially protonated form, or as acid or basic addition salts. Generally such peptide amphiphiles can be made by standard solid-phase peptide chemistry including addition of a hydrophobic tail at or near the N-terminus of the peptide. Modifications of these synthetic methods can be made as would be known to those skilled in the art and aware thereof, using known procedures and synthetic techniques or

straight-forward modifications thereof depending upon a desired amphiphile composition or peptide sequence. For example the hydrophobic tail is bonded to the amine group on the pendent chain of the lysine amino acid rather than the amine group on the chiral carbon.

Examples of the Invention.

The following non-limiting examples and data illustrate various aspects and features relating to the compounds, systems and/or methods of the present invention, including the self-assembly of various branched peptide amphiphile compounds having associated therewith one or more bioactive epitope sequences, such compounds as are available through the synthetic methodology described herein and through those co-pending applications incorporated by reference. In comparison with the prior art, the present compounds, systems and/or methods provide results and data which are surprising, unexpected and contrary thereto. While the utility of this invention is illustrated through the use of several amphiphilic peptide compounds, branched configurations and/or epitope sequences which can be used therewith, it will be understood by those skilled in the art that comparable results are obtainable with various other peptide compounds, and epitopes coupled thereto, as are commensurate with the scope of this invention.

Example 1

This example describes the preparation of peptide amphiphiles which include a branched peptide segment. (Reference is made to the aforementioned incorporated applications, and the synthetic detail provided therewith, in conjunction with Figures 6 and 7, below.) All of the peptides were synthesized by Fmoc Solid Phase Peptide Syntheses (Fmoc SPPS) protocol. Fmoc, Boc and 4-Methyltrityl (Mtt) protected amino acids, MBHA Rink Amide resin, and HBTU were purchased from NovaBiochem. The other chemicals were purchased from Fischer or Aldrich and used as provided. Peptides were constructed on MBHA Rink Amide resin. Amino

acid couplings were performed with 4 equivalents of Fmoc protected amino acid, 3.95 equivalents HBTU and 6 equivalents DIEA for 4 h.

Fmoc deprotections were performed with 30 % Piperidine/DMF solution for 10 min. Mtt removal was done with 1% TFA / Dichloromethane solution in the presence of TIS for 5 min. Cleavage of the peptides from the resin was carried out with a mixture of TFA:TIS in ratio of 97.5:2.5 for 3 h. The excess TFA was removed by rotary evaporation. The remaining viscous peptide solution was triturated with cold ether and the resulting white product was dried under vacuum. P A's were characterized by Matrix Assisted Laser Desorption Ionization-Time of Flight Mass Spectrometry (MALDI-TOF MS) and/or Electrospray Ionization Mass Spectrometry (ESI-MS).

Transmission Electron Microscopy (TEM) samples were prepared with I wt % gels of the PA's on a holey carbon coated TEM grid. Negative staining was done by 2% phosphotungstic acid solution. One wt % gels of PA's for TEM were prepared by mixing one to one 2 wt % PA solution in water and phosphate buffer (pH=7.4).

Initially, resin was swelled in DMF for 30 min and then Fmoc protecting group on the resin was removed by 30 % Piperidine/DMF solution. Then Fmoc-Lys (Mtt)-OH was coupled to the resin. Lysine side chain protecting group, Mtt, was removed by I % TFA/Dichloromethane solution without cleaving Fmoc protection. Palmitic acid (C_{16} alkyl chain) was coupled to the resin with amino acid coupling reagents. After completion of the palmitic acid coupling, Fmoc was removed by piperidine solution and amino acids which are the rod part of the PA were coupled in the same way (Fmoc SPPS).

Lysine was chosen to synthesize branches of the PA. Alpha and epsilon amine protection of the lysine was selected according to the branch design. If two different branches are desired, Mtt group was used for lysine side chain protection. For growing the first branch, Fmoc group was removed without removing Mtt protection. After completion of the first branch sequence, the last amino acid was selected with a Boc protection which is resistant to the Mtt

cleaving conditions. Then Mtt is removed to grow the second branch of the PA. If two similar branches was desired, Fmoc side chain protected lysine was used to make the PA. Both Fmoc groups were removed by piperidine solution, and the two branches of the PA were made at the same time.

Example 2

The series of molecules described below illustrates a novel branched PA architecture, designed to increase the accessibility of epitopes to receptors on nanofiber surfaces by using a bulky, sterically hindered peptide structure. The representative, non-limiting molecules contain lysine dendron moieties, and similar to other linear PAs of the type incorporated herein, self-assemble to form aqueous gels formed by a network of nanofibers. As shown in Figure 5, the molecules contain the peptide sequence KXXXAAAK (X=G or L) followed by a saturated sixteen-carbon alkyl segment, with the dendron branch introduced at a lysine residue. Alanine, glycine and leucine residues were used to promote hydrogen-bonded β-sheet formation, which should favor aggregation into extended structures such as cylindrical nanofibers, rather than into spherical micelles as is more typically observed in amphiphilic self-assembly. The well known biological epitope RGDS is present in cell binding domains of extracellular proteins such as fibronectin and vitronectin, and was used to illustrate incorporation of one or more of a range of bioactive peptides into such PA systems. The RGDS epitope is known to bind to integrin receptors, and this molecular recognition event plays a critical role in adhesion of cells to the extracellular matrix and in the complex cascade of signaling that follows.

Molecule 8 was synthesized with a linear peptide structure to compare epitope availability with that in branched PAs of this invention. A lysine residue was introduced to create asymmetrically branched molecules 9A and 9B, thereby altering structural presentation of the bioactive peptide sequence after self-assembly. Molecules 10A and 10B were synthesized to introduce symmetrical branches in a similar fashion to 9A and 9B, and to investigate the presentation of multiple epitopes by a single PA molecule. Furthermore, in

molecules 9 and 10, the effect of hydrophobic side chains on structural accessibility of the epitope was studied by exchanging glycine (R=H) residues with leucine (R = isobutyl) residues. To examine recognition and availability of epitopes, the RGDS sequence on each PA was terminated with a biotin group, and biotin accessibility was then probed using the binding of a fluorescein isothiocyanate (FITC)-labeled avidin molecule. It is well known that avidin has a very high affinity for biotin, with four biotin binding sites per protein. This binding affinity has been previously used to study surface availability of monolayers by varying the number of biotin moieties presented. Interactions between the fluorophore and amino acid residues in the biotin binding site of the avidin cause quenching of fluorescence. Therefore, binding of the biotinylated PA with fluorescently labeled avidin should lead to a significant fluorescence recovery by weakening the quenching interactions.

Example 3

The branched PAs were prepared using solid phase peptide synthesis (SPPS). Branching of the peptide segment was achieved by using orthogonal protecting group chemistry. (See, Bourel, L.; Carion, O.; Masse, H.G.; Melnyk, *O. J. Peptide Sci.* 2000, *45*,488-496; and Aletras, A.; Barlos, K.; Gatos, D. Koutsogianni, S.; Mamos, P. *J. Peptide Protein Res.* 1995, *6*, 264-270.) Fmoc, Boc and 4-methyl trityl (Mtt) protecting groups on the amines of the lysine residues were used to control the design of peptides, as each of these protecting groups can be manipulated independently. Fmoc protected amines were used to couple amino acids onto the peptide, Boc protecting groups were used to block lysine branches, and Mtt was used for selective deprotection and growth of asymmetrical branches. The RGDS epitope was coupled to the ε amine of the lysine residue to enhance the epitope's conformational freedom, due to the flexible four-carbon linker. Biotinylation of the PAs was achieved via SPPS by coupling a biotin to the end of the peptide sequence.

Example 4

All PAs were soluble in water at pH 4 and formed self-supporting gels at concentrations greater than 0.5 wt % when pH was increased above about 6.5.

Gel formation was found to be fully reversible with pH change. Transmission electron microscopy (TEM), atomic force microscopy (AFM), FT-IR and circular dichroism (CD) spectroscopy were used to characterize the self-assembly of branched PA molecules. TEM micrographs of self-assembled PAs 8-10 at pH 7.4 revealed the formation of uniform, high aspect ratio nanostructures with diameters of 7 ± 1 nm and ranging from hundreds of nanometers to several micrometers in length. The FT-IR of lyophilized (freeze-dried) gels of all PAs indicates hydrogen bonding between the peptides, based on N-H stretching peaks at 3280-3285 cm^{-1}. Amide I peaks at 1628-1632 cm^{-1} are consistent with a predominantly β-sheet-like character for the peptide secondary structure, with some α-helix and random coil conformations, indicated by peaks in the range of 1650-1675 cm^{-1}. Additionally, a shift of ν_a (CH_2) from ca. 2932 to ca. 2921 cm^{-1} indicates a high degree of ordering in the palmityl hydrophobic segment. Circular dichroism spectra from the self-assembled PAs reveals a broad peak ($n\pi^*$ transition) between 200 and 230 nm which can be interpreted as a signature for the predominant presence of β-sheets, as well as minor contributions from α-helical and random coil conformations. IR and CD results are consistent with a highly ordered assembly of hydrogen bonded PAs with β-sheet character, resulting in densely packed molecules within the nanofibers.

Example 5

Dilute samples of biotinylated PAs were prepared at pH 7.4 to investigate the influence of binding with FITC-avidin. Interestingly, a significant increase in fluorescence emission is observed upon binding of FITC-avidin to biotinylated branched PAs, relative to linear PA 8. This result suggests that, despite the structural similarity observed by TEM, FITC-avidin has greater accessibility to the biotin on the surface of nanofibers made up of branched molecules compared with those made up of linear molecules. In linear PA systems, dense hydrogen bonding may result in more compact packing of the epitopes on the surface of nanofibers, thus hindering binding of

FITC-avidin to biotin, resulting in less recovery of fluorescence emission. However in the sterically hindered branched systems, enhanced availability of biotin to the avidin receptor may indicate less effective packing of molecules on the fiber surface. In addition, incorporation of hydrophobic side chains on the PA structure altered the availability of the epitopes as well. Biotin availability on 9B and 10B was significantly higher than on 9A and 10A, respectively. Therefore, hydrophobic side chains in these molecules may also be affecting the nature of packing in the assembly and consequently epitope availability.

Example 6

As a control, non-biotinylated versions of PA 8 and 9B were prepared and tested with FITC-avidin under the same conditions. No significant change in the fluorescence of FITC-avidin was observed, indicating that the increased fluorescence is not due to non-specific avidin binding to the PA. These results confirm the proposed effect of branching and hydrophobic side chains on epitope availability at the periphery of the nanofibers. Biological experiments are underway to establish if structural differences in RGDS epitope presentation on the nanofibers influences in similar fashion the more complex recognition process of this peptide sequence by cells cultured with the peptide amphiphile nanofibers.

Example 7

As described and as provided in the aforementioned incorporated references, the peptide amphiphile compounds of this invention can be prepared so as to provide a structural polarity reversed according to convention. By comparison, solid phase synthesis typically requires that peptide segments be synthesized from the C-terminus to the N-terminus. As a result, such amphiphilic compounds have been prepared by capping the free N-terminus with an alkyl moiety, resulting in a compound with either a free acid or amide group at the C-terminus. Here, in contrast, for purposes relating to bioactivity or synthetic flexibility, it can be desirable to provide a peptide amphiphile with a free N-terminus. Accordingly, a synthetic route was devised to allow

introduction of a hydrophobic component on or about the C-terminus, and provide one or more pendant functional groups to effect branching and epitope coupling. Figures 6 and 7 schematically illustrate such synthetic modifications. With reference to Figure 6, the hydrophobic component (e.g., an alkyl moiety) is added before peptide growth, using orthogonal protecting groups. With reference to Figure 7, corresponding protection/deprotection strategies allow for creation of branching at one or more lysine residues, as well as selective epitope (e.g., RGDS) coupling, providing amine termination at the peptide periphery of a corresponding micellar configuration.

* * *

As the preceding illustrates, cylindrical nanostructures formed by branched peptide amphiphile molecules present high densities of surface binding sites. The branched covalent architecture of such molecules leads to greater accessibility of binding sites to a probing protein receptor, an observation useful in supramolecular design of bioactivity in synthetic nanoscale materials for biology and medicine.

We claim:

1. A non-linear peptide amphiphile compound comprising a peptide component comprising at least one amino acid residue comprising a pendant amino group, said amino group coupled to a component non-linear with said peptide component, said peptide component coupled to a hydrophobic component.

2. The compound of claim 1 wherein said residue is of a naturally-occurring amino acid.

3. The compound of claim 2 wherein said amino acid is lysine.

4. The compound of claim 3 wherein said peptide component comprises at least two lysine residues.

5. The compound of claim 4 wherein said non-linear component comprises a bioactive epitope sequence.

6. The compound of claim 5 wherein said epitope sequence is selected from RDGS, PHSRN, IKVAV, YIGSR and the recognition product of a phage display process.

7. The compound of claim 6 wherein each of said two lysine residues is coupled to one of said epitope sequences.

8. The compound of claim 1 wherein said peptide component comprises residues selected from alanine, glycine, leucine, cysteine and serine.

9. The compound of claim 1 wherein said hydrophobic component comprises an alkyl moiety ranging from about C_6 to about C_{22}.

10. The compound of claim 9 wherein said alkyl moiety is coupled to a lysine residue at about the C-terminus of said peptide component.

11. The compound of claim 10 wherein said peptide component comprises at least two lysine residues, at least one said residue coupled to a bioactive epitope sequence selected from RDGS, PHSRN, IKVAV, YIGSR and the recognition product of a phage display process.

12. The compound of claim 11 wherein at least one of said sequences is coupled to a spectroscopic probe component.

13. The compound of claim 11 assembled into a micellar

configuration.

14. A system comprising a non-linear peptide amphiphile compound comprising a peptide component, a hydrophobic component coupled to said peptide component, said peptide component comprising at least one amino acid residue comprising a pendant amino group coupled to a bioactive epitope sequence, said compound in a fluid medium.

15. The system of claim 14 wherein said residue is of a naturally-occurring amino acid.

16. The system of claim 15 wherein said amino acid is lysine.

17. The system of claim 14 wherein said epitope sequence is selected from RDGS, PHSRN, IKVAV, YIGSR and the recognition product of a phage display process.

18. The system of claim 17 wherein said hydrophobic component is coupled to an amino group pendant to said peptide component.

19. The system of claim 18 wherein said peptide component comprises residues selected from alanine, glycine and leucine.

20. The system of claim 17 wherein said medium is at a physiological pH, said system comprising an assembly of said compounds.

21. A method of using a pendant amino group of a peptide amphiphile to present a biologically active epitope sequence, said method comprising:

providing a plurality of peptide amphiphile compounds, each said compound comprising a hydrophobic component and a peptide component, at least one of said compounds comprising at least one amino acid residue comprising a pendant amino group; and

coupling a biologically active epitope sequence to said amino group.

22. The method of claim 21 wherein said peptide component comprises a lysine residue at about the N-terminus thereof.

23. The method of claim 22 wherein said epitope sequence is selected from RDGS, PHSRN, IKVAV, YIGSR and the recognition product of a phage display process.

24. The method of claim 22 wherein the N-terminus of said peptide component comprises two lysine residues.

25. The method of claim 24 wherein each of said residues is coupled to an epitope sequence selected from RDGS, PHSRN, IKVAV, YIGSR and the recognition product of a phage display process.

26. The method of claim 22 wherein said compounds are in an aqueous medium, and the pH of said medium is adjusted to assemble said compounds in a cylindrical micelle.

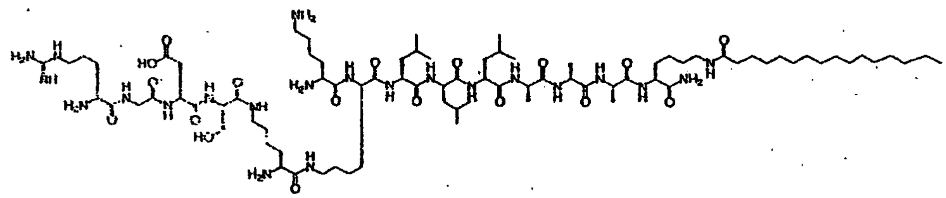
27. The method of claim 21 wherein at least one of said compounds comprises a peptide component comprising at least two lysine residues.

28. The method of claim 27 wherein each of said residues is coupled to an epitope sequence selected from RDGS, PHSRN, IKVAV, YIGSR and the recognition produce of a phage display process.

29. The method of claim 28 wherein one of said residues is coupled to an RDGS epitope and one of said residues is coupled to a PHSRN epitope.

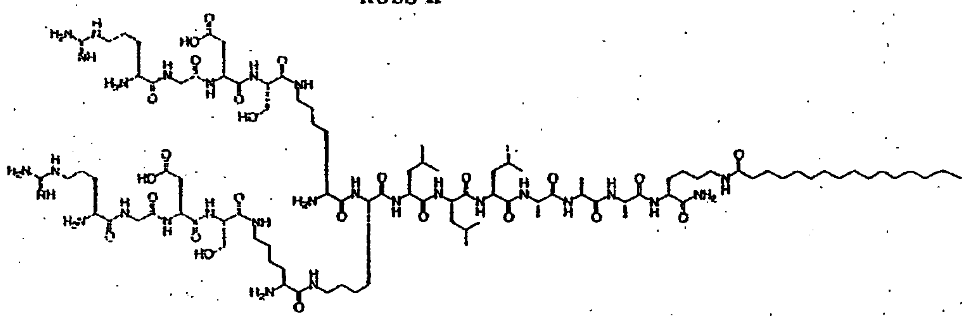
30. The method of claim 29 wherein said compounds are in an aqueous medium and assembled using a reagent in said medium.

K
RGDS-K K--LLL--AAA-(K)--C16



1

RGDS-K
RGDS-K K--LLL--AAA-(K)--C16



2

RGDS-K
PHSRN-K K--LLL--AAA-(K)--C16

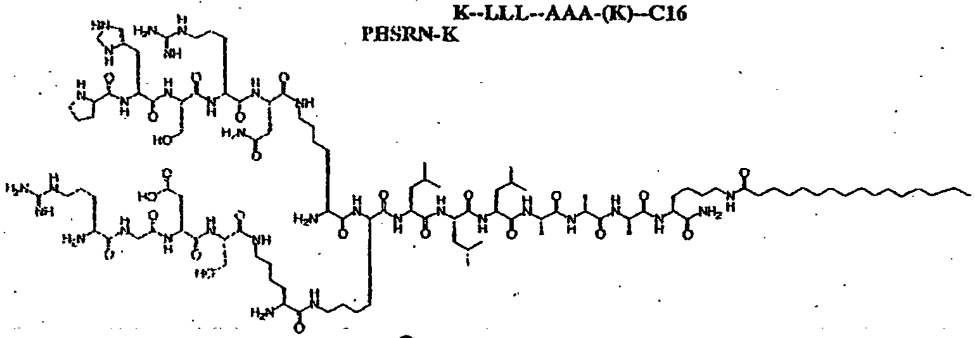


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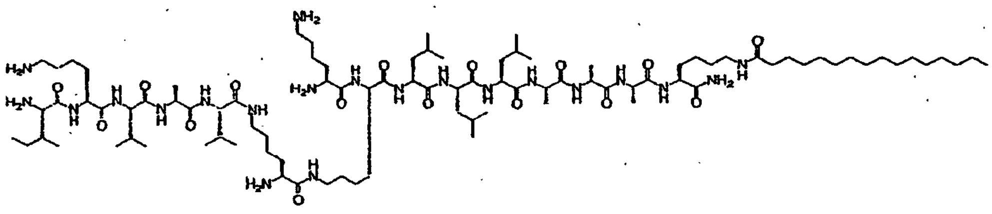
Figure 1.

IKVAV-K
K--LLL--AAA-(K)--C16
K



4

IKVAV-K
K--LLL--AAA-(K)--C16
YIGSR-K

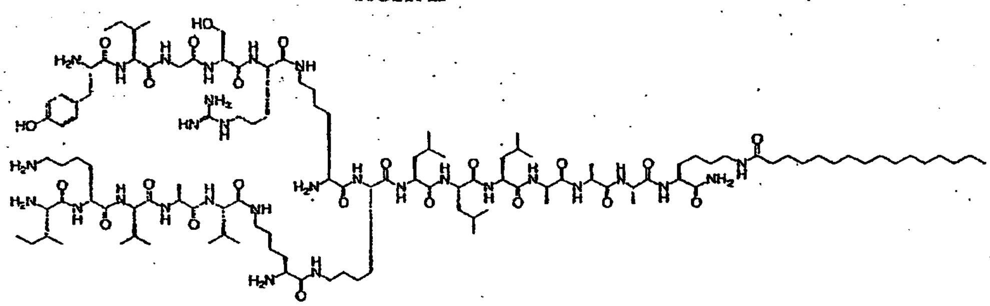


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Figure 2.

K
K--LL--CCCC-(K)--C16
K

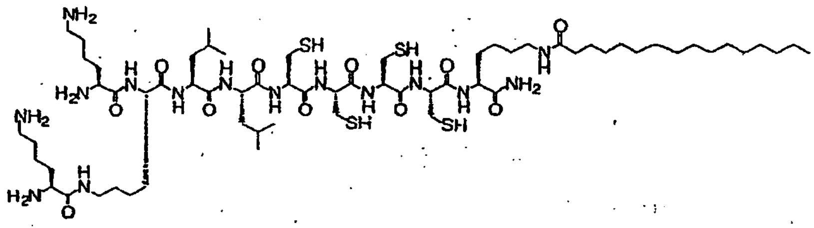

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Figure 3. Highly positive charged Branched Peptide Amphiphile 6.

DOTA--KG-RGDS-K
K--LLL--AAA-(K)--C16
K

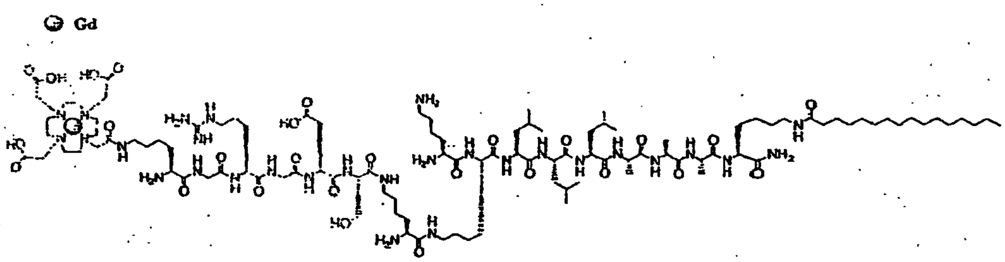

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Figure 4.

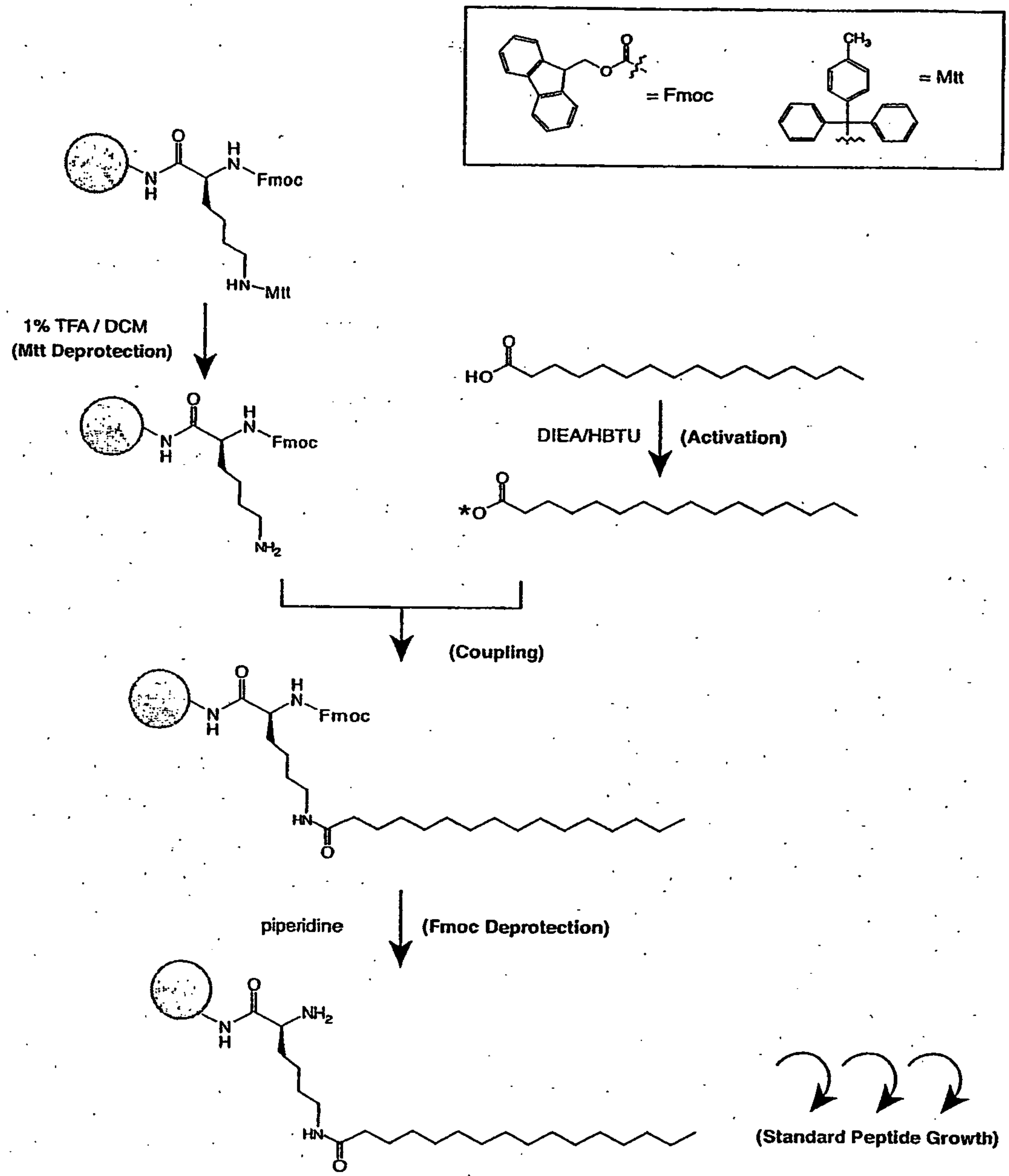
= Fmoc
= Mtt
Fmoc
HN~Mtt
1% TFA / DCM
(Mtt Deprotection)
HO
DIEA/HBTU
(Activation)
*O
Fmoc
NH_2
(Coupling)
Fmoc
HN
piperidine
(Fmoc Deprotection)
NH_2
HN
(Standard Peptide Growth)

Figure 6

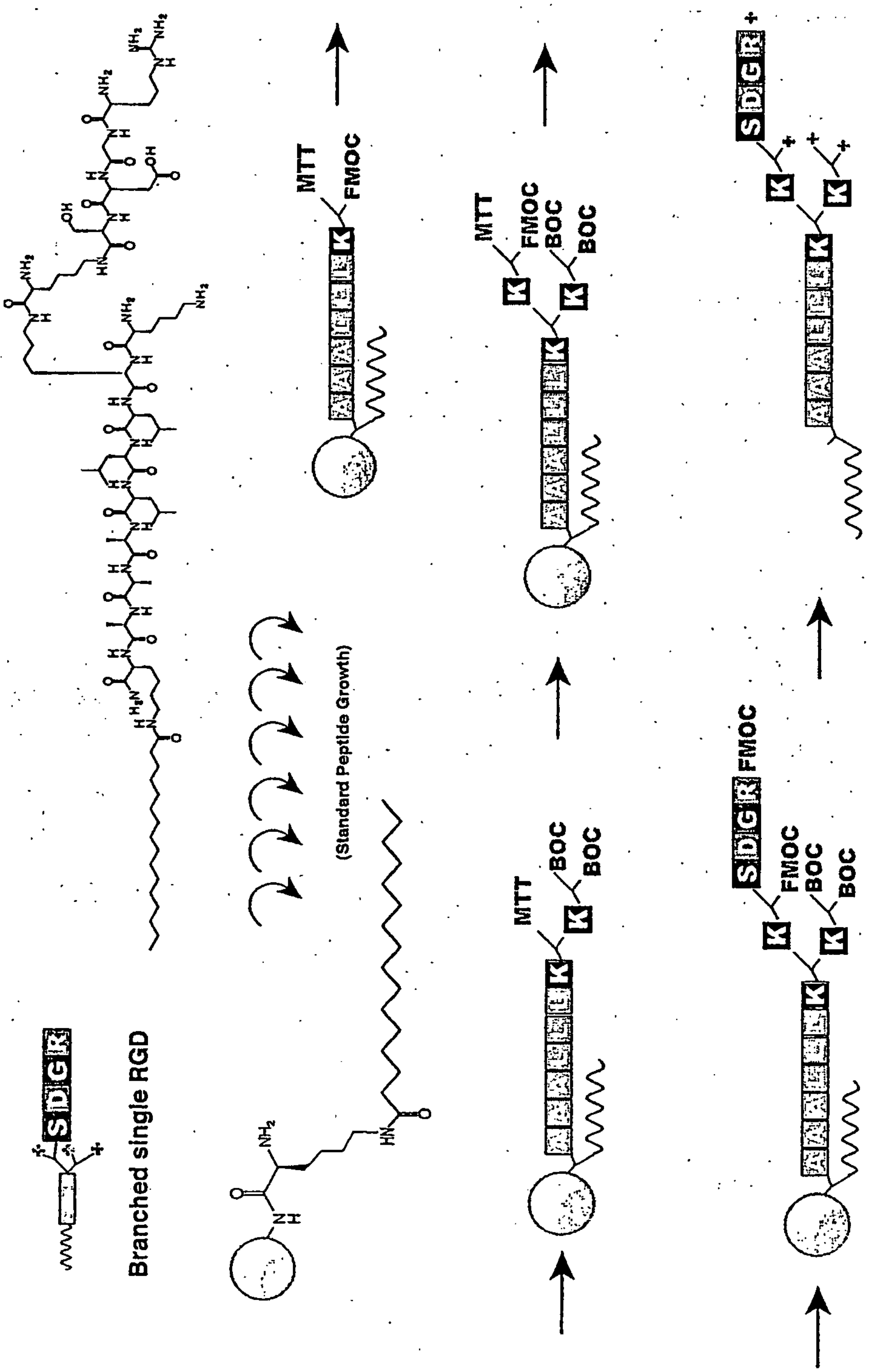
Branched single RGD
(Standard Peptide Growth)
MTT
FMOC
BOC
BOC
SDGR
K

Figure 7